EVALUATION OF THE ZFX 240-kJ PARALLEL-PLATE WATER CAPACITOR: LESSONS LEARNED[†]

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ABSTRACT

The ZFX pulsed-power generator employed a unique intermediate store capacitor; a 0.58-μF water-dielectric parallel-plate transfer capacitor (TC) designed for a maximum voltage of 940 kV. To lower the cost and overall size of the TC, plastic field attractors (PFAs) were used to reduce the electric field in the water at the plate edges. The TC was operated successfully at the 750 kV level for several discharges, but a damaging electrical breakdown in the TC ended operations. Electrical stress in the TC was well below the predicted failure level at the time of the breakdown; it was probably caused by debris in the water. Debris was particularly difficult to remove because of the complicated geometry of the TC, a factor which also impeded removal of trapped air bubbles and limited accessibility of the TC interior. PFAs had poor survivability when a fault occurred. The extensive engineering and fabrication effort required to correct these problems would reduce the possible cost savings of the configuration.

DESIGN RATIONALE

ZFX was a 250-kJ pulsed power generator,[1,2] designed and partially built as a driver for z-pinch fusion experiments. It was later completed in anticipation of its use for plasma opening switch (POS) work. The initial projection of the generator's performance was 1 MA delivered to a load in 500 ns, based on circuit modeling[3,4] with estimated electrical parameters. The novel feature of ZFX was its intermediate-store capacitor, a parallel-plate water-dielectric transfer capacitor (TC).[2] This design offered low inductance, low cost, and was relatively compact. In fact, it was the only design that could provide the desired performance and fit the budget and space constraints. It also represented a high technical risk, as the chosen configuration was unproven on such a large scale. Unfortunately, the TC suffered a damaging electrical breakdown before reaching its desired performance. Many practical difficulties were discovered and overcome in bringing the TC into operation; this experience is presented here.

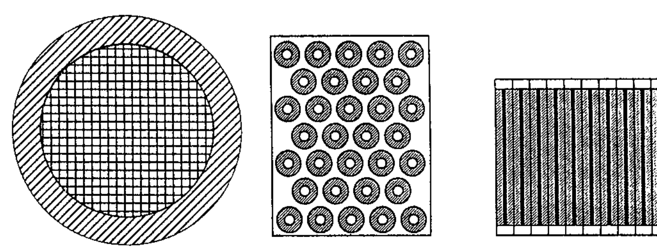

Figure 1. Three possible water capacitor configurations.

Cross-sections of three possible configurations for a water capacitor are compared in Fig. 1. The single coaxial line is well understood and relatively simple in construction. However, the large volume inside its center conductor does not store energy, and thus is wasted space. An array of many coaxial lines in parallel, as used on DECADE,[5] is a more space-efficient arrangement than a single line, allowing a more compact, low-inductance TC. But the fabrication and assembly of such a complex device would appear to make this the most expensive option. A third possibility is the parallel plate capacitor, with flat high-voltage and ground vanes arranged in an open-topped rectangular water tank. This configuration is the most compact for a given stored energy; compared with a DECADE-module water capacitor, a comparable parallel-plate water capacitor could be 20% smaller in volume.[4] Most of its components could be easily fabricated from standard-size metal and plastic stock. The difficulty with a parallel plate configuration is the enhancement of the electric field at the plate edges. This must be reduced to prevent electrical arcing through the water and to take full advantage of the configuration's space efficiency.

ZFX used plastic field attractors[2] (PFAs) to reshape the electric field at the edges of thin high-voltage vanes.

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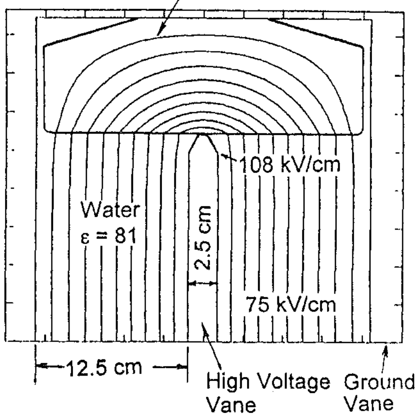


Figure 2. Electric field at a ZFX high-voltage vane edge and plastic field attractor; applied voltage is 940 kV.

The much lower dielectric constant of the plastic (2-3 versus 81 for water) redistributes, or "attracts," the electrostatic equipotential surfaces, reducing the field in the water. Figure 2 shows the equipotential lines around a vane edge and PFA, as generated by an electrostatic field solver. The field values shown correspond to the initial-design maximum TC voltage of 940 kV. Without the PFA, the electric field at the vane tip would be 340 kV/cm in the water. With the PFA in place, this field is reduced to 170 kV/cm, and it now occurs inside the plastic rather than in the water. The highest field in the water (108 kV/cm) occurs at the end of the vane edge-taper. The field away from the edges is very uniform; 75 kV/cm over the 10^6-cm^2 area between the vanes.

DESIGN DESCRIPTION

The equivalent circuit for ZFX (Fig. 3) is quite conventional; a 14-stage oil-insulated Marx generator stores 245 kJ at 50 kV charge. At this charge voltage the Marx charges the TC to about -750 kV in 2.5 μs. The transfer switch, a self-breaking rimfire-type gas switch, then closes and transfers current through an insulating vacuum feed-through to the load: 800 kA in 650 ns. As the TC discharges, an externally-triggered divertor switch is fired to damp-out ringing between the TC and the load.

The ZFX TC was constructed in two mirror-image halves, each a 2.9-m long by 2.4-m wide by 1.5-m high rectangular tank with an open top. Figure 4 is a photograph of the TC halves; between them can be seen a smaller tank which holds current collector plates, the transfer and divertor switches, and the load region. Eight high voltage vanes are supported vertically in each half. Figure 5 shows a cutaway drawing of a portion of the left TC half. The edges of the high voltage vanes are surrounded by the PFAs: solid blocks of plastic with a cross section of 10.2-cm high by 27-cm wide. Ground vanes separate each high-voltage vane and its respective PFAs. All vanes were of irridite-coated aluminum plate, 2.5-cm thick for the high voltage vanes, and 1.3-cm for the ground vanes. These thicknesses were chosen to ensure that the vanes had sufficient mechanical strength to survive a water breakdown without distortion. The ground vanes are bolted to the tank walls. The high-voltage vanes of each TC half are electrically interconnected through the ground vanes by insulated cylindrical feed-throughs. Parallel-plate current feeds, with their edges surrounded by PFAs,

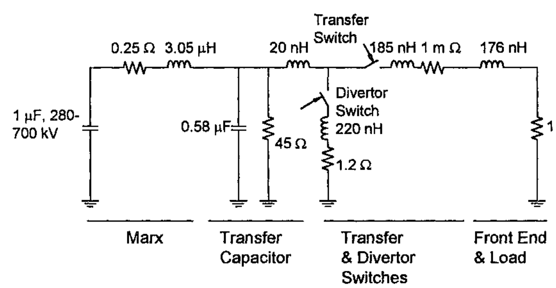


Figure 3. ZFX equivalent circuit.

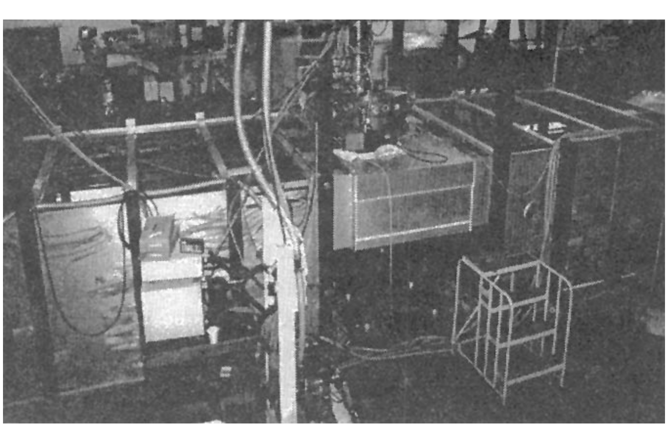


Figure 4. Photograph of ZFX transfer capacitor; the collector region is at center, Marx feed is at right.

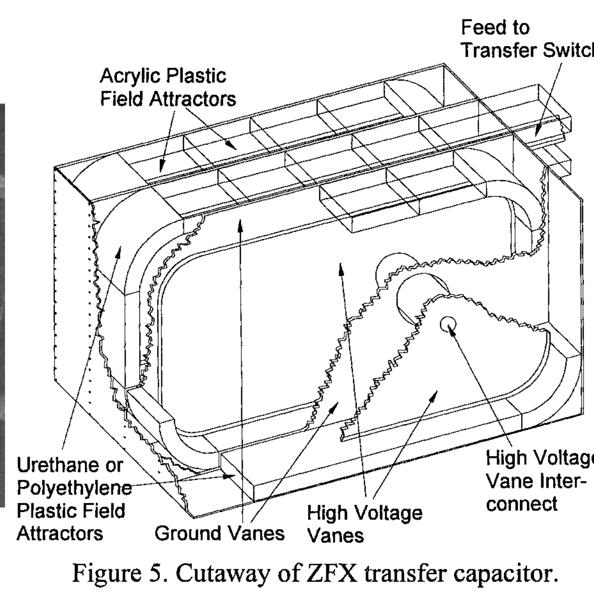


Figure 5. Cutaway of ZFX transfer capacitor.

lead into the collector plate in the central tank between the two TC halves. The transfer switch, vacuum insulator, and load region rose vertically from this plate in a coaxial configuration. The divertor system was connected to the bottom of the collector plate. The Marx generator fed into the high voltage vanes at the outside end of one of the TC halves, through an acrylic insulator.

ELECTRICAL BREAKDOWN LIMITS IN WATER

The empirically derived expressions for maximum allowable electrical stress in deionized water, formulated by J.C. Martin and others,[6]

$$E_+ = \frac{230}{\tau_{\mathrm{eff}}^{1/3} A^{.058}} \ (\mathrm{kV/cm}) \qquad (1)$$

$$E_- = \frac{560\alpha}{\tau_{\mathrm{eff}}^{1/3} A^{.069}} \ (\mathrm{kV/cm}), \qquad (2)$$

where $\alpha = 1{+}.12\sqrt{E_{max}/E_{mean} - 1}$,

were used to determine the operational voltage limit of the TC. $\boldsymbol{E}_+$ and $\boldsymbol{E}_-$ are the electric field levels, at the positive and negative electrodes respectively, that will cause a breakdown through the water. $\boldsymbol{A}$ is the electrode area under consideration (in cm^2) and the "effective time," τ_{eff}, is the time (in μs) that the absolute value of the applied voltage, $\boldsymbol{V}$, is above 63% of $\boldsymbol{V}_{max}$, its maximum value. $\boldsymbol{E}_{max}$ and $\boldsymbol{E}_{mean}$ are the maximum and mean electric fields present for a given geometry.

In applying equations (1) and (2) to an oscillatory system, it is assumed that a streamer will form during the first half-cycle of the TC voltage oscillation, and will continue to grow during each subsequent half-cycle without collapsing at the voltage zero-crossing points. To model this, a total τ_{eff} is determined for the entire oscillatory pulse. Each half-cycle (numbered in sequence as integer i) is first considered separately. For the first ($i = 1$) half-cycle, a value of $\tau_{eff}(i = 1)$ is calculated as the time that $\boldsymbol{V} > 63\%$ of $\boldsymbol{V}_{max}$ during this half-cycle. Then a $\tau_{eff}(i > 1)$ is calculated for each subsequent half-cycle as the time during that half-cycle that $\boldsymbol{V} > 63\%$ of $\boldsymbol{V}_{max}$. In each case, $\boldsymbol{V}_{max}$ is taken as the peak TC voltage from the first half-cycle. Later half-cycles in which the voltage damps out to the point that $\boldsymbol{V}$ never exceeds 63% of $\boldsymbol{V}_{max}$, are neglected. A total τ_{eff} is calculated for the entire voltage pulse by summing the individual τ_{eff} values, after applying a scaling factor[4] to the τ_{eff} values derived from the voltage reversal half-cycles. An example of this procedure follows.

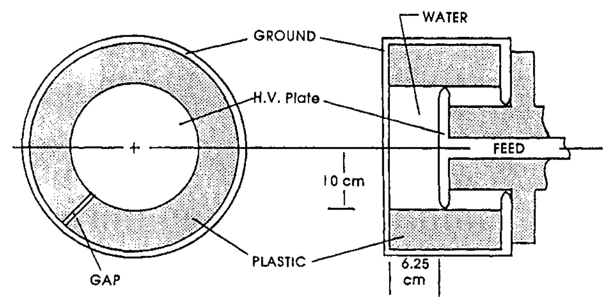
The likelihood of breakdown is considered separately in two different electrode-surface regions of the TC, with $\boldsymbol{V}_{max} = 940$ kV as in Fig. 2. First, the parallel-plate electrode surfaces are of concern because of their very large surface area ($\boldsymbol{A} = 10^6$ cm^2). The associated field in this region is uniform and perpendicular to the plates.. Because the electric fields are equal (75 kV/cm) on both electrodes, the lower value of the breakdown field, $\boldsymbol{E}_+$, is used as an estimate of the breakdown level between the plates. Since the first voltage half-cycle on the TC is negative, this assumes that an ionized streamer will originate from a ground electrode.

In the first half-cycle, $\boldsymbol{V}_{max} = 940$ kV; the time that $\boldsymbol{V} > 590$ kV (63% of $\boldsymbol{V}_{max}$) is 1.45 μs = $\tau_{eff}(i = 1)$. In the second half-cycle, $\boldsymbol{V} > 590$ kV for 0.40 μs = $\tau_{eff}(i = 2)$. None of the subsequent half-cycles exceed 590 kV. While $\boldsymbol{E}_+$ is valid during the first half-cycle, $\boldsymbol{E}_-$ describes the conditions in the second half-cycle, so $\tau_{eff}(i = 2)$ is multiplied by a scaling factor, $\boldsymbol{s}_-$, to compensate for the different coefficients in equations (1) and (2). The total τ_{eff} is $\tau_{eff}(i = 1) + \boldsymbol{s}_- \times \tau_{eff}(i = 2)$, where $\boldsymbol{s}_- = (230\boldsymbol{A}^{.069}/560\alpha\boldsymbol{A}^{.058})^{1/3}$. $\boldsymbol{A} = 10^6$ cm^2, and since the field here is uniform, $\boldsymbol{E}_{max} = \boldsymbol{E}_{mean} = 75$ kV/cm, giving $\alpha = 1$. The scaling factor is $\boldsymbol{s}_- = 0.78$, and the total $\tau_{eff} = 1.76$ μs. Using this in Eq. (1) gives a breakdown level of $\boldsymbol{E}_+ = 85$ kV/cm at $\boldsymbol{V}_{max} = 940$ kV. The ratio $\boldsymbol{E}_{max}/\boldsymbol{E}_+ = 0.88$. Thus, at a TC voltage of 940 kV, the transfer capacitor is operating at 88% of its breakdown limit between the parallel plates.

The second electrode-surface region of concern is the $\boldsymbol{A} = 5000$ cm^2-area of the high-voltage vane edges, where the highest electric field in the water is present ($\boldsymbol{E}_{max} = 108$ kV/cm, see Fig. 2). Here, the field is not uniform between the electrodes; it drops to the $\boldsymbol{E}_{mean} = 75$ kV/cm level a few centimeters away from the vane edge. In this case the high voltage vane is the negative electrode during the first half-cycle, so $\boldsymbol{E}_-$ is applied to model a streamer originating from this region. From Eq. (2), $\alpha = 1.08$, so $\tau_{eff}(i = 2) = 0.40$ μs for the reversal is corrected by $\boldsymbol{s}_+ = (560\alpha\boldsymbol{A}^{.058}/230\boldsymbol{A}^{.069})^{1/3} = 1.34$ to scale it to $\boldsymbol{E}_-$. The total τ_{eff} is 2.00 μs. Substituting this total τ_{eff} in Eq. (2) results in $\boldsymbol{E}_- = 267$ kV/cm. This gives a ratio of $\boldsymbol{E}_{max}/\boldsymbol{E}_- = 40\%$ at the high-voltage vane edges, much lower than that for the area between the parallel plates. Thus it should be the large area between the plates that will dominate the TC breakdown characteristics.

One other area of concern in the TC was the effect of water-filled gaps between adjoining PFA segments. These gaps would inevitably be present because of machining and assembly tolerances on the PFAs. In fact, a water-filled gap of some width is essential because it would be virtually impossible to remove trapped air from between PFA segments that are in direct contact with each other. A half-scale model of the corner of a high voltage vane and its PFAs (Fig. 6) was pulsed to high voltage to determine experimentally the maximum permissible gap size. The results were difficult to interpret clearly; the model would sometimes stand off many pulses at a voltage equivalent to 1 MV on the full size ZFX. On other occasions the system would breakdown at an equivalent voltage as low as 750 kV. However, these breakdowns were not necessarily in the PFA gap.

Three-dimensional electrostatic computer-simulation of a vane and PFA assembly showed that the electric field in such a gap rises rapidly with increasing gap size. Compared to a region with no gap, the field is 18% greater in a 3 mm gap and 28% greater in a 6 mm gap. Guided by the computer simulation results, and by the qualitative results from the half-scale test model, the PFAs were machined so as to maintain a water-filled gap of 1.3-mm between each segment. This was the minimum size that permitted the gaps to be inspected and cleared of trapped air bubbles. Care was taken to ensure that the machined surfaces of the PFAs were free of tool marks or other scratches, because it was observed that breakdowns on the half-scale model tended to follow machining grooves on the plastic surface. Also, it was decided to limit the TC voltage to about 750 kV for the first operational runs on ZFX.



Scaling to full size: $2 \times 0.75 \times 0.69 = 1$
(scale) $(\tau_{eff})^{1/3}$ (area)$^{.069}$

Figure 6. Half-scale test model of plastic field attractor.

ENGINEERING DEVELOPMENT ISSUES

A lesson learned early in the process of bringing ZFX into operation was that the TC and PFAs were very sensitive to small imperfections. Air bubbles in the TC were a constant problem; circulating the water through a vacuum deaeration system was inadequate. The locations where PFA segments came together in a horizontal plane inevitably trapped air when the tank was filled. By introducing a 1.3 mm gap in these locations, the joints could be inspected for bubbles with a commercially-available underwater viewing-scope. Bubbles could be swept out of the gaps with a small custom-built water jet.

Bubbles regularly appeared in the TC during operations. One source of bubbles was gas evolved at the current-carrying joints of the high-voltage vane interconnect. These bubbles were generally seen trapped beneath the upper PFAs, which were made from clear acrylic sheet to allow visual inspection of the TC interior. The other PFA segments were polyurethane, used for custom molded sections, or pressure-cast ultra-high molecular-weight (UHMW) polyethylene sheet. Lower cost materials, such as low density polyethylene, were subject to voids in the interior that resulted in an arc through the plastic.

Access to the interior of the TC was a major problem; very little of it could be reached directly by hand. When interior parts had to be removed or replaced, it was often necessary to disassemble large portions of the device. This was not uncommon because when a breakdown occurred across a PFA, it caused the plastic surface to become carbonized, necessitating repair by remote handling techniques or replacement. Because the original design did not take into account rapid assembly and disassembly, these operations could take several weeks. If the TC had to be drained, the process of removing air bubbles upon refilling was extensive. The convoluted nature of the vanes, PFAs, current feeds, switches, and tank support structure was one reason for the poor accessibility of the TC; another cause was limited funds that had precluded a more amenable engineering design.

Another difficulty was the buildup of debris in the water. The constant need for inspection and bubble removal meant that permanently closing over the top of the tank was not an option. Debris was observed in the tank, usually settled out on the upper surfaces of the bottom PFAs. Vacuum cleaning of this area was awkward and only marginally effective. Filters in the water circulation system were also ineffective. The close fit between the PFAs and the vanes (see figures 2 and 5) effectively divided the TC into a series of baffle chambers; water could only be injected or exhausted from outside these baffles. Water had to circulate around the edges of the PFAs, making it impossible to have a sufficient flow rate in the interior volumes to entrain and flush out trapped debris.

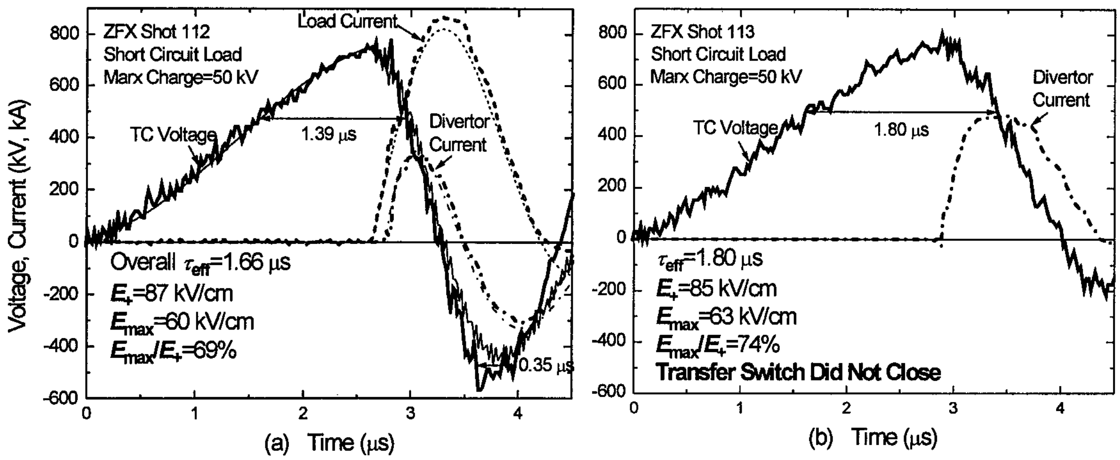


Figure 7. ZFX transfer capacitor voltage, load and divertor currents for shots with no water breakdown. Thin lines in figure 7a represent circuit modeling of shot 112.

ZFX was operated with an aluminum-wire array plasma-radiation-source (PRS) load, and a short circuit load of comparable inductance. Shot 112 is illustrated in Fig. 7a; the peak TC voltage, V_{max}, reached 750 kV without a breakdown,. Applying equations (1) and (2) to this shot as described above, E_{max}/E_{+} = 69% between the parallel plates. On shot 113 (Fig. 7b) the transfer switch failed to close, resulting in the highest electrical stress ever placed on the TC: E_{max}/E_{+} = 74% with V_{max} = 790 kV. Again, no breakdown occurred. Two shots which did have TC breakdowns are illustrated in Fig. 8. The operating conditions for shot 121 (Fig. 8a) were identical to those of shot 112, but jitter in the transfer switch closing lengthened the first voltage half-cycle on the TC. The TC broke down at the first voltage reversal. E_{max}/E_{+} = 69% at this time, as on shot 112; V_{max} = 765 kV for this shot, and τ_{eff} = 1.6 μs before the breakdown. Shot 104 (Fig. 8b) was fired with a lower Marx charge than the other shots in figures 7 and 8; V_{max} reached only 590 kV. However, a divertor switch triggering problem permitted the TC voltage to ring through two complete cycles, and the TC broke down late in time; E_{max}/E_{+} was only 59% in this case. After a PFA was destroyed on shot 121, ZFX operations ceased. The machine has since been dismantled.

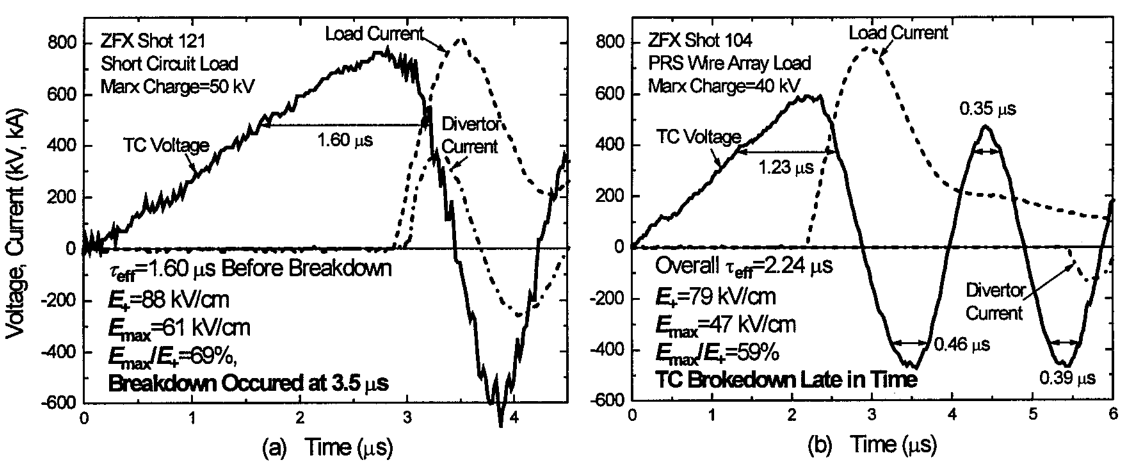


Figure 8. ZFX transfer capacitor voltage, load and divertor currents for shots with water breakdowns.

Triggering the divertor switch at the required time was difficult because of the shape of the TC voltage waveform and the fact that there was no inductive isolation between the divertor and the transfer switch. The divertor switch had to standoff the maximum TC voltage, then breakdown while the TC voltage was dropping rapidly. Jitter in the operation of the self-triggered transfer switch made the timing of this event difficult to predict.

Premature triggering of the divertor caused a significant reduction in load current, but late triggering could result in excessive voltage ringing on the TC, leading to water breakdown. On some shots the divertor trigger command came too late, and the divertor did not fire until the first or second TC voltage reversal. A method of generating the divertor trigger command by sensing the rise of the load current was being developed when ZFX operation ceased. This required a backup trigger command timed from the beginning of the shot, in the event that the transfer switch failed to close.

While the parallel plate TC achieved its low-inductance goal of 20-nH, the performance of the transfer switch was disappointing. Its inductance was originally estimated at 50 nH, but circuit modeling[3] (see Fig. 7a) showed that its actual inductance was 185 nH. This, along with the reduced charge voltage, prevented ZFX from achieving its desired load current performance.

CONCLUSIONS

The most likely cause of the TC breakdowns on shots 104 and 121 was debris on the surface of the PFAs. Both breakdowns occurred at the upper surface of the polyethylene PFAs on the bottom of the tank, where debris had been seen to accumulate. In both instances the breakdown track damage was across the surface of the PFA, rather than penetrating through it, and arc damage was seen on the high voltage vane about 5 cm above the PFA surface. This would be near the location of the maximum electric field present in the water.

Keeping the water of the TC clear of debris and bubbles is greatly complicated by the convoluted geometry of a parallel-plate water capacitor with PFAs. To properly circulate and filter the water, it is vital to establish a flow rate sufficient to flush out debris in the otherwise stagnant water pockets. One possible approach to this problem would be a system of inlet and outlet manifolds built inside the ground vanes, but this would make them thicker and more complex. Another method would be to reshape the cross-section of the PFAs, creating a gap between their outside edges and the ground vanes that would be sufficient to circulate water at a high flow rate. The electrical requirements of redistributing the electric field would still have to be met by the new PFA shape. As long as access is required through the top of the TC, it might also be necessary to build the device in a clean room environment to reduce the introduction of debris. None of these solutions was practical on ZFX, and the need for them was not fully understood until after it was learned how sensitive the PFA system is to small imperfections.

The problem of removing air bubbles from the TC was solved on ZFX, but at a very high cost in labor. By making PFAs in large segments rather than from multiple smaller pieces, the air-trapping horizontal PFA joints could be eliminated. These large segments could be custom cast from polyurethane, but they would be much more expensive and more awkward to handle than the ZFX PFAs. Another vital improvement needed for a parallel plate TC is improved access to the interior. TC construction should be modular, so that a single vane, PFA, or switch can be removed or serviced without significant disassembly of the rest of the machine.

The parallel-plate water capacitor is an attractive idea for high energy systems. However, the advantages of compactness and the perceived simplicity of its components must be weighed against the inherent complexities of the design. The tight spaces, trapped water volumes, susceptibility to debris, and the non-self healing nature of surface discharges on plastic make this task a challenge. The expense of the engineering and fabrication effort required to create a practical, maintainable device could significantly reduce the cost benefits that the configuration holds. Also, the electrical breakdown characteristics of a large-area PFA-equipped parallel-plate water capacitor have yet to be tested in a debris-free environment. Unfortunately, work on this concept has ceased and these issues remain unresolved.

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